Reprogramming Fuel Injection—Part One: Orientation

In the fuel injection age, this is how tuning is done. No more jets and needles, just grids and keyboards.

The Times, They Are A-Changin'

Back in May of '01, I wrote a lengthy article comparing four jet kits and two dynamometers used in assessing their performance. The test mule was a Honda CBR600F4, with a bank of four CV carburetors. Before starting that project, I'd fiddled with a couple of dirt bike carbs and installed one four-cylinder jet kit, sticking to the recommended settings that came with it. But I'd never done any systematic tuning or made use of dyno charts.

I was emboldened to take on that project by the fact that I'd be working with two tuning experts who would walk me through their respective methodologies for extracting the best possible performance out of each jet kit. The impetus for testing those kits was the installation of an aftermarket exhaust system and air filter on the CBR, each of which would theoretically allow it to breathe more freely, with two potential results: First, *without* carb tuning, the mixture might have been too lean, compromising performance and possibly causing the engine to run hotter. And second, *with* carb tuning, improved performance might be achieved, as the increased volume of incoming air could then be paired with more fuel which, if correctly balanced, ought to generate more power when ignited.

During the course of testing many different combinations of needles, needle heights, mixture screw settings and jet sizes, I grew nauseatingly familiar with that brace of carbs. We did dozens and dozens of dyno runs, making adjustments between most of them. Numerous seat-of-the-pants adjustments were made, too. Remember, all those changes involved doing the same thing to *four* carbs. By the end, I could remove, disassemble, reassemble and replace those carbs blindfolded (well, almost).

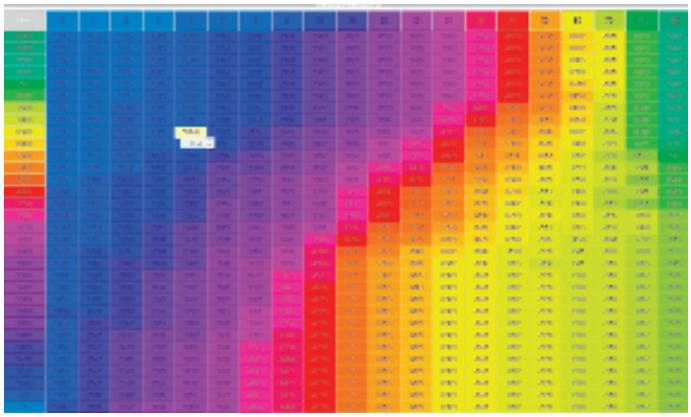
Although this was an excruciatingly tedious process (I'm literally shuddering at the memory of it), I certainly developed a good understanding of how each of the possible adjustments affected fuel flow at different throttle positions, and how to listen and feel for signs of a lean or rich mixture. And I learned how dyno testing can inform the tuning process, including the auxiliary use of exhaust gas analysis to monitor and evaluate the actual air-fuel ratio being delivered by the carbs at any given engine speed. Still, I'd never, ever want to do it on that scale again.

As I write this, I feel a strange uneasiness, like when I catch myself using the word "album" while discussing music, or "film" in a conversation about photography—two domains the digital revolution has radically changed forever. I don't want to think of myself as someone so old that I can recall a truly bygone era, and we're not quite yet at the point where discussions of carburetors must be accompanied by an explanation of what those ancient contraptions were, but the day is coming. Computerized fuel injection (EFI) is no longer a novelty in the motorcycling world; it is steadily advancing across product lines. Of course, it took over the entire automotive realm long ago. For better or for worse, we're in the midst of a mass carb-ocide.

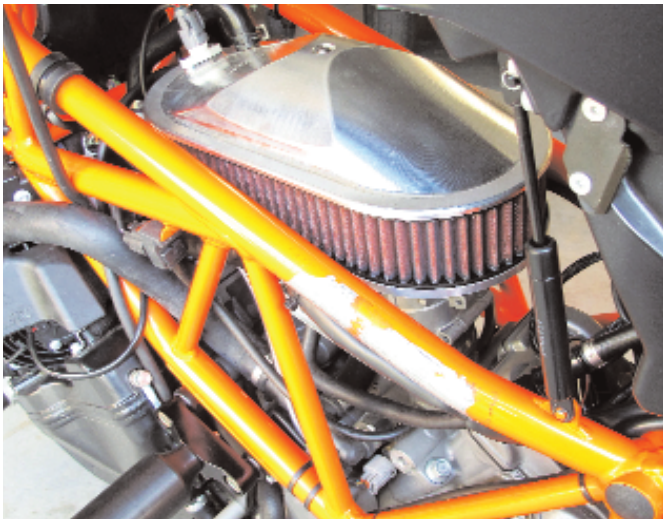
So What's a Poor Tuner to Do?

At first glance, it might seem that the carburetor's extinction may leave shade-tree tuners with no option but to either accept their bikes' factory-dictated digital scripts or pay a tuner for his sophisticated understanding of the electronics involved—and the use of his expensive specialized equipment. Regardless of how well a lay person might comprehend the fueling process, it's no longer possible to translate such knowledge into performance gains with a few hand tools and an assortment of jets and needles. EFI tuning requires the ability to tap into the "black box" brain of the motorcycle; its Engine Control Unit (ECU). This means having certain hardware and software, and knowing how to read and write the digital "maps" that have come to replace physical needles and jets in managing fuel delivery.

It turns out things really aren't so bad. More and more companies are making electronic modules that simply plug into



Along the top are TPS values as % open. Along the left side are rpm points. Where each column and row intersects is the injection duration for that unique combination. The white cell is ready to be edited. Note: This map is from tuning software that will be presented in the next installment, not from the PC-III.



Stock airbox left, MotoHooligan airbox, right—Compare the little nostrils on the stock airbox's snorkel to the wrap-around breathability of the MotoHooligan. Which do you think the LC8's cylinders would prefer?

a bike's wiring harness. These devices can alter the ECU's interpretation of incoming information from sensors, and modify its instructions to the fuel injectors (some also include the ability to alter ignition timing, coordinate with optional quick shifters, traction control add-ons, and more).

Some are simply "plug-and-play," containing a model-specific pre-programmed map proffered as superior to the stocker, perhaps designed for use with the most common airflow-enhancing mods (e.g., a slip-on exhaust canister and freer-flowing air filter). Others allow for some basic alteration of the fuel mixture, such as enriching it to various degrees at the bottom, middle or top of the rpm range. And some, when connected to a computer running the associated software, allow for extensive fueling modification at a large number of specific throttle-position/rpm combinations. A select few, with the addition of auxiliary wide-band oxygen (O_2) sensors, can even "learn" how to massage injector instructions to achieve individually specified air-fuel ratios for each one of those combinations, with separately tailored maps for each cylinder and each transmission gear, and user-defined fueling adjustments for different speed, temperature and air pressure ranges! But most are much simpler *(whew!)*.

In sharp contrast to hours of carb dis- and re-assembly, custom tweaking of EFI sounds too good to be true. Simply connect your laptop, execute a few well-chosen mouse-clicks and keystrokes, and *voila!*, you're done! Not only is this worlds easier and quicker than swapping jets and needles, it can be much cheaper, too. As we'll show you later in this series, it's possible to significantly improve some bikes' EFI performance with hardware that costs less than the price of the average single-cylinder jet kit. And keep in mind that, when you hire a tuner and/or buy dyno time to gather hard data for the dialing-in process, the meter would also be running during all that carb R&R. You might recover the entire cost of your EFI mods in saved tuner/dyno charges, compared to what you'd spend on those pro services for carb tuning.

Instead of jets and needles, then, the aspiring fuel-injection tuner will have to manipulate numerical tables that influence how much fuel the injectors force into the airstream entering the engine. While this may seem intimidating to the uninitiated, it's actually more straightforward than tuning carbs in some ways, and is definitely within the reach of many—perhaps most—home mechanics. I'm speaking as one who had even less preparation for this project than I had for the jet kit comparo. The only fuel injection "tuning" I'd ever done before was to confirm the calibration of my old Suzuki TL1000S's Throttle Position Sensor (TPS), a task that I vaguely recall as requiring only a #2 Phillips-head screwdriver and the ability to read LCD numbers on the bike's gauge cluster.

So, I admit that embarking on this mission called to mind those "Messin' with Sasquatch" commercials (see YouTube if you missed them). I worried I might thoroughly confuse the bike's brain, and possibly even do irreversible damage to its electronics—or worse, the motor itself (overly lean mixtures can cause overheating and piston damage). But even if my foolish tinkering could provoke terrible consequences, the idea that I might accomplish far more than I did with those carbs, just by tapping a keyboard, was irresistible. And, rather than having to understand stuff about the fluid dynamics of venturis, needle tapers, and jet orifices, all I had to focus on was a single variable: the length of time an injector was open during the intake cycle.

This is the beauty of digitalization: everything's reduced to 1 or 0, on or off. The end product of all the ECU's calculations is how long an injector will flow fuel, an event that occurs for mere milliseconds. Basically, each injector is a solenoid-operated valve with pressurized fuel on one side and the bike's intake tract on the other. When the ECU commands the injector to open, it opens completely; when instructed to close, it closes completely. The only variable for controlling mixture is how long it stays open. And, rather than having to figure out how to blend transitions from a carb's idle circuit to its needle taper to its main jet size, there's just a grid of numbers, with engine rpm along one axis and throttle position along the other. Cells in the grid represent all possible combinations of these variables, and contain numbers that define injection duration for each of those combinations.

True, an ECU may take into account other variables, too, such as atmospheric pressure, air and engine temperatures, O_2-sensor readings, etc., each of which contributes a map of its own to the calculation process. For example, a cold engine temp bumps mixture instructions toward the rich side (lengthening injection duration), making an airflow-restricting choke obsolete. But tuning (at the level described here) isn't concerned with all those inputs and calculations. It's only concerned with the ultimate *output*—the injection duration grid; that's what gets tweaked. The only exception is the signal from the O_2 sensors (if present), which may have to be negated in order for an aftermarket module to work its magic.

The stock catalytic converter forms the Y-pipe connecting the 2-into-1 header with the two slash-cut canisters. It's gorgeously sculpted, but terribly heavy and sounds very sedate.

FMF's carbon-fiber/titanium Apex canisters are very light, and not only because of their exotic materials; they contain precious little to quiet the LC8's roar.

Of course, the question remains: How can we tell what numbers should go in all those cells to optimize performance? And how, exactly, do we go about changing them? These and other questions will be addressed in future installments. But before we get into solutions, we need to understand the problems; good prescriptions are based on good diagnoses. To illustrate various EFI issues, we'll be using a lightly modified 2007 KTM 990 SuperDuke (actually 999cc).

The Problem Child: Beauty and Beast

Our SuperDuke presents two kinds of challenges. First, there's the stock map. Just like most fuel-injected motorcycles, this one came from the factory with less-than-ideal mapping. Although engineers may start with a map that maximizes engine performance, achieving compliance with emission and noise regulations, along with goals for fuel economy, can require distortions of that original schema. The same is true for carbureted bikes. A jet kit or a revised ECU map can "undo" such distortions and allow even an otherwise unmodified bike to run better.

But unlike carbureted bikes, most fuel injected motorcycles suffer to varying degrees from an additional malady: startlingly abrupt on/off throttle response, not unlike the ultra-crisp illumination of LED brake lights and turn signals (regular incandescent bulbs seem to be on dimmer switches, by comparison). The resulting engine misbehavior is especially problematic for a bike with exceptionally brawny power right off idle and very responsive handling. You *do not* want a SuperDuke bucking hard during delicate throttle manipulations while heeled over in a tight corner! The resultant effect is the polar opposite of "confidence-inspiring!"

Secondly, just like the CBR in that jet kit article, our test bike has received airflow-enhancing modifications that could yield an overly lean mixture without fueling adjustments. Or, at the very least, their potential benefits (beyond weight reduction and aesthetic appeal) are likely to remain unexploited. But wait, you might ask, doesn't fuel injection do a terrific job of automatically and precisely maintaining optimal air-fuel ratios under widely varying conditions for which carburetors would need re-jetting, such as big changes in altitude? Why can't it do the same with intake and exhaust mods?

The short answer is this: Most EFI systems on motorcycles today, while capable of detecting and compensating for things like changes in altitude, won't notice the impact of intake and exhaust mods on the fuel mixture because they're not "looking" for it. The long answer involves a discussion of open-loop and closed-loop EFI designs; look for that in a subsequent installment. For now, you'll have to take it on faith that common modifications to a fuel-injected motorcycle's intake tract or exhaust system will likely require mapping changes to maximize performance and reliability.

Although magnificent in many ways, KTM's big V-twin, designated the "LC8" across an array of bike models, lost something in the translation from its original 950cc carbureted form to the current 999cc fuel-injected iteration. The 950s were known for superlative throttle response, with smooth, clean fueling from idle to redline. The 999s gained a little strength, but at the expense of some finesse. The LC8 was never a particularly graceful motor, with its ultra-light flywheel and über-punchy power. KTM's slogan, "Ready to Race," could have been revised to "Ready to Launch" for LC8-equipped models. Actually, make that "Ready to *Lurch*" for the fuel-injected versions, at least in terms of off-idle behavior.

Because our test mule was fitted with several aftermarket accessories by its previous owner, we don't know exactly how this particular one behaved when new. We have, however, ridden SuperDukes and other fuel-injected LC8s of this vintage in stock form, and read and heard numerous owner accounts. We've concluded that it's pretty common for these bikes to suffer from not only abrupt off/on throttle response, but also some surging below 4000 rpm, as well as a little "hunting" at steady highway speeds, none of which is all that unusual for a fuel injected bike.

In addition to these EFI-related fueling glitches, SuperDukes inhale through a seemingly small and restrictive airbox. We haven't measured its volume or flow, but we find it hard to imagine those two big cylinders, gulping at high rpm, being fully satisfied by what could squeeze through that airbox's dainty snorkel. And SuperDukes exhale through an enormous (and very heavy) catalytic converter, cleverly tucked under the seat with two rather quiet (read "stuffy") canisters.

Hidden from view inside each throttle body (that part of the fuel injection system that goes where the carburetor used to be) are another set of obstructions some argue deserve removal, the secondary butterfly valves (metal disks that flip open and closed like a traditional choke) and their shafts. These are now common on many fuel injected bikes, and are supposed to smooth power delivery by modulating the rate at which air flow into the engine changes. They're operated by the ECU via a servo motor. Whereas the twist-grip can yank open the main butterflies via the

Above—The Secondary Air Injection plumbing serves no purpose with the catalyst removed, so it was jettisoned as well.

Right—Removing the SAI isn't a free mod; you'll need Moto-Hooligan block-off plates for the locations where it used to enter each cylinder head.

throttle cables almost instantaneously (limited only by the speed of a rider's wrist), the ECU may intervene by easing open the secondary butterflies more slowly. Theoretically, this results in smoother throttle response, prevents the hesitation of a momentary lean condition, and maintains optimal airspeed through the throttle body.

Detractors say that, when it comes to airflow, more is always better (provided adequate fuel is available). They want as little as possible getting in the way of incoming air, and they sure don't want a computer deciding how suddenly they're allowed to go wide open. These folks insist that removing the secondary butterflies results in a noticeable increase in power, and attribute that to more air flowing less turbulently through the throttle body. Secondary butterfly defenders counter that this modification only creates the sensation of more power because it makes throttle response more sudden (something we certainly don't want on this bike at low rpm, where the secondary butterflies have their biggest impact).

We could probably do a whole article on this debate, collecting objective data about this modification in isolation and drawing a definitive conclusion. Instead, we'll just outline the arguments here, and relay a really surprising claim made by many posters on internet forums: removal of the secondary butterflies and their shafts *reduces* on/off throttle snatch, not only for fuel injected LC8's but other makes and models, too. We can imagine that a secondary-ectomy might improve top-end horsepower because of improved airflow (especially given how the SuperDuke's don't quite open all the way to vertical), but we can't come up with any explanation for reduced snatch off idle—if anything, it ought to make snatch worse. See page 31 to learn what we *actually* experienced when we tried it.

While not contributing to any airflow impedance, the Secondary Air Injection system (SAI or SAS)—a solenoid-controlled collection of hoses that helps the catalyst finish burning any fuel that snuck through the combustion process unspent by adding fresh air to the exhaust tract—adds complexity and plain old ugliness to the breathing apparatus. Switching to a non-catalytic exhaust system makes the SAI unnecessary for engine function and another candidate for removal.

At this point, a disclaimer is in order: We cannot recommend that readers modify their motorcycles in ways that may violate legal mandates. And we appreciate that some may not want to alter anything that could make their bikes less environmentally friendly. Nevertheless, we're well aware that a multitude of motorcyclists make minor intake and exhaust mods of exactly the sort we're about to describe. If you're concerned about the legality of such modifications, consider this series relevant for closed-course track use only. If it offends your environmental sensibilities, consider it applied science.

As mentioned earlier, this particular SuperDuke came to us already sporting an assortment of typical interventions and accessories. Those affecting the engine were as follows:

Starting with the intake tract, the stock airbox had been replaced with a beautifully crafted (and accordingly priced) billet aluminum piece by the aptly named MotoHooligan Performance, an outfit devoted to fixing the quirks and enhancing the performance of KTM's infamous hooligan machine (see their website for applications of these parts to other LC8-equipped bikes, and even Harley V-Rods). Sandwiched between the machined aluminum plates is a free-flowing K&N air filter. The whole setup looks like something that would be at home under the hood scoop of a 1960s-era American muscle car, and it adds an invigorating "honk" to the music emanating from the engine bay during heavy breathing.

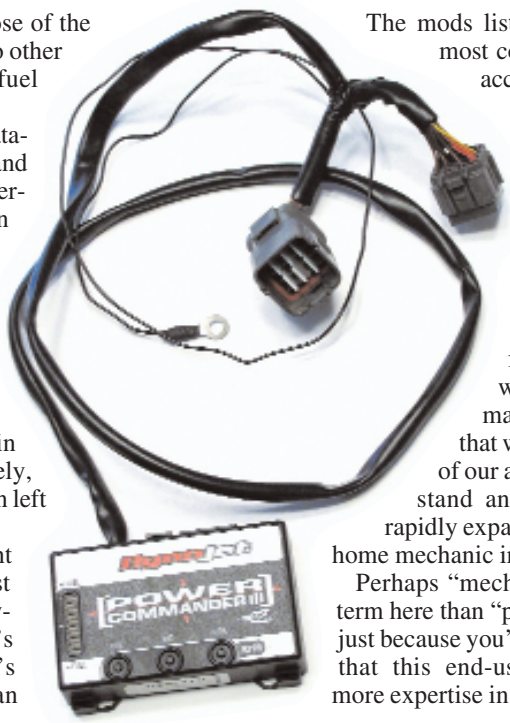
Note: You can find YouTube videos (just search for "Moto-Hooligan") wherein owners have tried to capture this wonderful noise, but—just as with any rich motorsport sound recorded with less-than-studio-quality audio equipment—what comes through is only a tiny slice of the aural spectrum. The videos are still worth looking up, however, because several show the secondary butterfly servo doing its thing. When viewing the throttle bodies from the left, you'll see two linkages that move with each blip. The lower (controlling the main flies) moves abruptly, while the upper (for the secondaries) lags fluidly.

On the other side of the combustion chambers, the stock catalyst and canisters were replaced with FMF Apex slip-ons. These carbon-fiber/titanium units save a lot of weight, complement the SuperDuke's origami styling with their sharply angular geometry, and allow exhaust gases easier exit. The cost of these benefits (in addition to their lofty purchase price), is *noise!* Even with the supplied inserts (small conical tubes that are supposed to reduce the decibels), these cans are obnoxiously loud, even to those who would otherwise appreciate their raucous, *basso profundo* voice. We've heard about a fix for this (perforated sheet-metal, custom-welded across the insert openings), and hope to try it out; we'd love to be able to retain the Apex cans, but they're way too loud for street use. If we succeed in quieting them down,

we'll give you a full report. For the purpose of the current project, though, we're confident no other slip-ons would threaten to lean out air-fuel mixtures more than these.

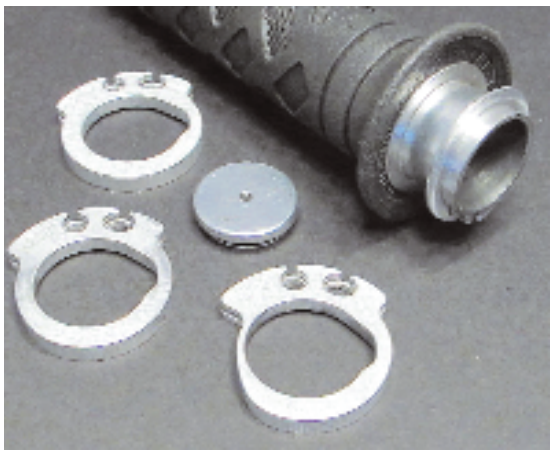
As mentioned earlier, removal of the catalyst allows for removal of the SAI, too, and ours had been taken off. This required aftermarket block-off plates (also MotoHooligan pieces) to seal the openings on each cylinder head where the SAI had been connected. The ECU will turn on the EFI warning light and generate an error code unless it's either tricked into thinking the SAI is still functioning (by bridging the now-unplugged electrical connector with a resistor), or by disabling the SAI circuit in the ECU (see next installment). Alternatively, the plumbing and wiring could have all been left in place, and the hoses simply plugged.

To address the lean condition that might have resulted from these intake and exhaust mods, and in the expressed hope of remedying the stock fueling flaws, our SuperDuke's previous owner had also installed Dynojet's Power Commander III-USB (PC-III), an add-on module that modifies the ECU's instructions to the injectors. This had been loaded with Dynojet's "advanced" map for SuperDukes with aftermarket exhausts and air filters. An Akrapovic full exhaust system and a BMC air filter are specified in this map, but it was the closest match for the bike's mods, given what few pre-set options Dynojet offers. It could reasonably be expected to get this SuperDuke's fueling well within the ballpark.



Above—Dynojet's PC-III is a tidy add-on that's easy to use. Read about it in the next installment.

One other mod bears mentioning. In his attempt to tame the SuperDuke's abrupt throttle response at very low rpm through a purely mechanical intervention, the previous owner had replaced the stock throttle tube with G2's Throttle Cam System, allowing for exchange of the stock profile to others that ramp up more gradually during the first half of throttle rotation, offering the rider more control within that range. The most gradual cam was installed. We've reviewed the G2 system before (February 2009), and it makes a noticeable difference. Switching back and forth between cams on the SuperDuke revealed a slight advantage to the softer cam profile. However, mechanical fixes don't get to the root of the problem of throttle snatch, which—as we'll illuminate in upcoming installments—lies buried within the KTM's EFI.



Above—G2's throttle cams lock onto the end of their aluminum throttle tube, allowing quick modification to the speed of the throttle reaction in the first half of twist-grip rotation.

Now What?

If this were a product evaluation, we'd now turn our attention to what differences, both objective and subjective, each of these pieces made to our SuperDuke's performance. But this isn't that kind of article. Our focus here is on fuel injection and what options exist for you as a consumer in your efforts to optimize it.

The mods listed above are merely exemplars, the most common types of performance-oriented accessories installed by average motorcyclists. They set the stage for our exploration of what ordinary folks can do to re-mix a bike's fueling in the post-carburetor era.

In upcoming installments, we'll show you what's involved in using a PC-III, as well as two alternatives, with attention to how to maximize your DIY capabilities, and when to get professional assistance. A small portion of what we'll discuss is specific to KTM machinery; after all, it's an LC8's fueling that we're trying to perfect. But the majority of our attention will be spent on how to understand and employ some examples from the rapidly expanding range of gadgets available to the home mechanic in pursuit of EFI nirvana.

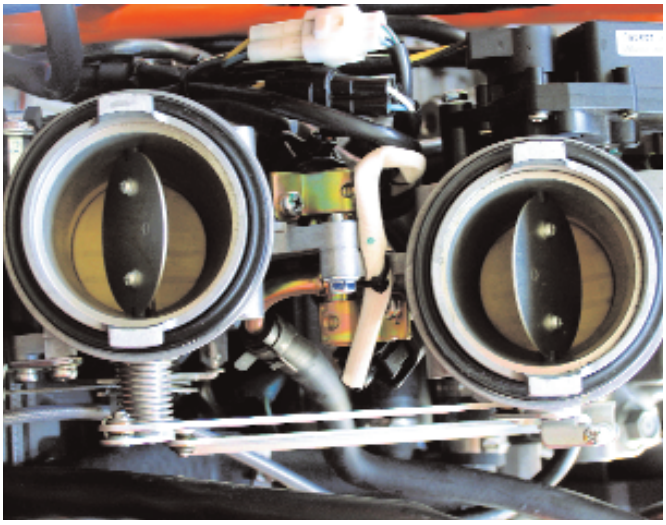
Perhaps "mechanic" would seem a less appropriate term here than "programmer." But don't be intimidated just because you're not a computer engineer. It turns out that this end-user technology doesn't require any more expertise in electronics and software than those jet kits required in the area of fluid dynamics—maybe even less.

FLY AWAY (secondary butterfly, that is)

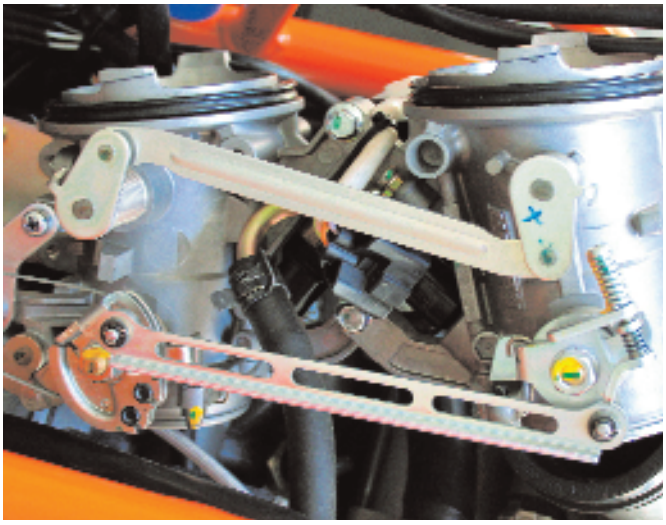
Because of the multitude of testimonials on various LC8-related forums (and elsewhere) advocating secondary butterfly removal as a means of reducing on-off throttle snatch, and the way said snatch seriously detracted from the joy of riding our SuperDuke, we began our quest for improved fueling here—even though it seemed seriously counter-intuitive.

The procedure was straightforward. After removing the airbox, lifting the throttle bodies (assembly intact) out of their rubber boots, and stuffing rags in the intake tracts to keep out debris, the first step was to remove the screws holding the disks to their shafts. For some reason, KTM opted to make these screws out of wax and weld them in place. Okay, not really. But they're almost impossible to remove without rounding out. Some internet posters stopped here, leaving the shafts in place and saving themselves most of the work. Others replaced the stock circular disks with more elliptical ones from MotoHooligan that allow more flow in the closed position. We decided to go all the way, and remove everything.

This involved unplugging the electrical connection and removing the screws that hold the servo motor in place, along with its TPS (separate from the one for the main flies), and pulling the combo away from the throttle bodies. Small pieces tried to fall out and get lost; be warned. Next, we removed the circlips on the right-side shaft ends, and slid the linkage assembly (with shafts attached) away from the throttle bodies on the left side. This was a bit nerve-racking, as the shafts proved very hard to budge at



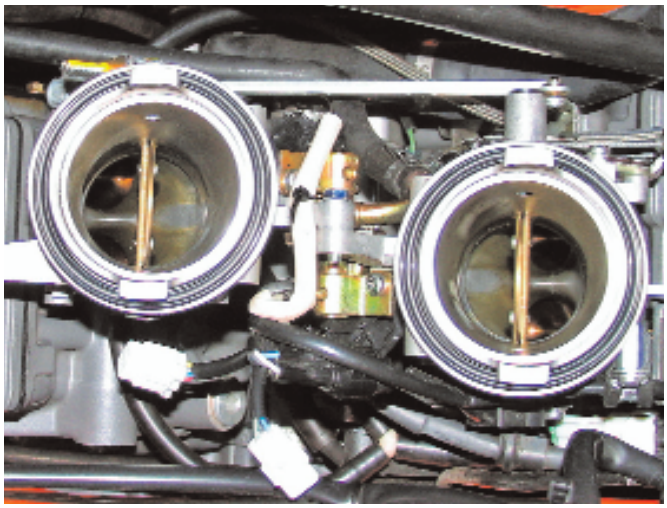
Above—The computer-controlled secondary butterflies are seen here partially open. Even fully open, they're not quite vertical, creating what would seem to be a significant obstruction to incoming airflow. The main butterflies, controlled by the twistgrip, are visible closed beneath them.



Linkage at bottom is controlled by the throttle cable, and rotates the main (lower) butterflies. Upper linkage transfers movement from the servo-controlled rear secondary butterfly to its forward mate. The upper linkage, as well as the servo motor and its TPS will all be removed.

certain points along the way and required considerable force; they finally surrendered with no harm done.

Finally, the holes left by the shafts had to be plugged. We used some plastic automotive trim panel fasteners with a wide cap that would prevent them from being sucked in by those huge pistons at 9500 rpm, and wrapped them in Teflon tape to give just the right interference fit. Then we buttoned everything back up. The whole process is easily reversible, but doing so involves resetting the removed TPS, which is a pain (see the factory service manual).



Above—Secondaries removed, main butterflies open, the view down through the throttle bodies is clean and uncluttered.

Note that removal of the secondary butterfly TPS will produce an error message and turn on the EFI warning light; the ECU will detect its absence. As the ECU has a set of maps devoted to operating the secondary flies—and assumes they're part of the equation, its calculations for the main butterflies will be thrown off, even if only the plates are removed. There's a way to "turn off" the secondary butterflies in the ECU to address these issues, but that'll have to wait until the next installment.

So what did we notice with the secondary butterflies removed? There really was a small, but definitely noticeable, reduction in the jerkiness of on/off throttle transitions. Under close scrutiny, this seemed to be mainly a matter of less dramatic engine braking during the on-to-off transition; the bike no longer felt quite so much like it'd been caught by a tail hook. The off-to-on transition didn't seem to be any different, or at least the difference was so small as to likely be the product of suggestion. But it certainly wasn't any worse, either, and worse is what we would have expected. So, given the lack of any apparent penalty for their removal, and the likelihood that (at least high-rpm) performance would be enhanced by cleaning up the intake tract, we left them off. As it so often turns out, less is more.

Sources

Motobox with K&N Air Filter, $348.49; SAS Blockoff Kit (with resistor),$34.95; LC8 Secondary Butterflies, $24.95; MotoHooligan Performance, 1210 Commerce Court #4, Lafayette, CO 80026; 720-371-6747; www.motohooligan-performance.com

Apex Slip-on Exhaust Canisters, $1099.99; FMF Racing, 18033 South Santa Fe Avenue, Rancho Dominguez, CA 90221; 310-631-4363; www.fmfracing.com

Power Commander III-USB (model 925-411), $399.95; Dynojet Research, Inc., 2191 Mendenhal Drive, North Las Vegas, NV 89081; 800-992-4993; www.dynojet.com

G2 Throttle Cam System, $109.95; G2 Ergonomics, 1008 East Commercial Street, Lyndon, IL 61261; 815-535-3236; www.g2ergo.com

Note: Check online for substantially lower prices on all but the MotoHooligan items.